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Assessment of the Performance of Osmotically Driven Polymeric Membrane Processes

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Abstract

The universal water scarceness and the extensive ordeals with energy cost in conjunction with the undesirable ecological effects have advanced the improvement of novel osmotically driven membrane processes. Membrane processes which are osmotically driven are developing type of membrane separation procedures that apply concentrated brines to separate liquid streams. They are adaptable in various applications; hence, allow them to be an attractive substitute for drug release, wastewater treatment and the production and recovery of energy. Although, internal concentration polarization (ICP) occurs in membrane practises which are osmotically driven as a consequence of hindered diffusion of solute in a porous stratum, their interest has even increased. Here we review two natural membrane processes that are osmotically driven; Forward osmosis (FO) and Pressure retarded osmosis (PRO). Thus, the major points are as follows: 1) it was highlighted in this review, that the major developments in FO process, important for the process efficiency is to choose a suitable membrane and draw solution. 2) The recent evaluation, understanding and optimizing the activities of fouling throughout the osmotic dilution of seawater employing FO was discussed. 3) Recent advancements of FO in the application of food processing was reviewed. 4) It was highlighted that the main concept of PRO for power generation is the energy of mixing that offers great assessment of the non-expansion work which could be generated from mixing; nonetheless, the development of effective membranes with appropriate arrangement and performance is needed for the advancement of PRO process for power generation. 5) One major challenge of osmotically driven membrane processes, most recent developments and model development to predict their performances were discussed.

Keywords: Forward osmosis. Pressure retarded osmosis. Membrane orientation. Energy. Desalination

1. Introduction

Regarding the increase in industrial activities around the globe, water and energy are considered as global utmost significant resources. The unavailability of water and predicaments of energy have weighed down most societies world-wide [1]. Water and energy are in fact, inseparably as they associated to one other. The production of freshwater and making it available for the society requires a lot of energy, and the generation of power regularly needs a huge quantity of water [2] and many districts globally have huge demands for fresh water [3]. Osmotically driven membrane (ODM) processes has revealed excellent prospect in the production of clean water supply and energy together with the applications of food processing and medical products and applications [4]. Membrane processes aided by pressure need the application of hydraulic pressure with the employment of electricity, having a great value and progressively costly form of energy. All these requirement resulted to the development of membrane processes that are osmotically driven. Membrane processes that are osmotically aided depend on transmembrane osmotic pressure which occurs via a concentrated draw solution or osmotic agent [5]. Thus, membrane processes that are osmotically driven are developing type of membrane separation procedures that employ concentrated brines to separate liquid streams. Membrane processes that are osmotically driven are FO [6], PRO [7], osmotic membrane bioreactor which is an emergent process incorporating a FO process into a membrane bioreactor [7], [8]. The recent progress of these membrane processes that are osmotically driven have dared conventional methods based on their substantial prospect in different types of applications. This review therefore, summaries some of the features of this processes with regard to some crucial issues and perceptions. Some applications of these osmotically driven membrane processes were further discussed together with their recent developments, challenges and the importance of theoretical models.

2. Forward osmosis (FO)

FO process employs the gradient of the osmotic pressure as aiding strength; hence, is considered an energy-saving membrane separation process [9]. Since the forward osmosis process mechanisms depend on osmotic pressure, one of the most important components that should exist with the interest of enabling the process to take place efficiently is known as draw solution. Draw solution (DS) denotes concentrated solution present in the permeable part of the membrane; it acts as the power-cycle aiding the force in forward osmosis process [10]. This process contains the utilization of a concentrated DS to draw water across the membrane from a feed solution (FS). The difference of the osmotic pressure between the two solutions is a function that aids the strength for permeation across the membrane [11]. Thus, such process need not an application of hydraulic pressure like RO process. Permeation of water from the feed solution will eventually dilutes the concentrated DS that will departs from the membrane module as a diluted DS. The advantages of forward osmosis are a lesser fouling propensity, much more water recovery and minor working conditions. Forward osmosis is principally a suitable application for processes that occur with undesired re-generation of the draw solution, for example, irrigation and hydration bags. This is because water has the ability to be transferred, devoid of external forces [12]. These membranes have distinctive characteristics that aid effectual diffusion of water across the polymer. For a desirable FO membrane, the following properties are important: extremely hydrophilic, with numerous pores; nonetheless they have sufficient strong support layer that will reduce the influences of internal concentration polarization (ICP). Furthermore, they have ultrathin defect-free selective layer that is high and has the capacity to attain intense water flux, salt rejection that are high enough and reduce reverse solute diffusion [13]. Solvent flux in FO is aided by chemical potential difference amid two solutions, which is exhibited by the osmotic pressure differential ($\Delta\pi$) via the thin, semipermeable membrane amid a hypertonic draw solution and a feed [14]. The osmotic pressure of a solution is given as:

$$\pi = \frac{RT}{V_A}\ln(a_A) \tag{1}$$

where, R stands for ideal gas constant, T stands for absolute temperature, V_A denotes molar volume of the solution, and a_A stands for activity of the solution (*1*). Flux (J_w) in FO is commonly expressed as:

$$J_w = A(\pi_{draw,mem} - \pi_{feed,mem}) \tag{2}$$

where A denotes membrane water permeability coefficient, $\pi_{draw,mem} - \pi_{feed,mem}$ denotes effectual osmotic pressure through the selective support of the FO membrane. Eq. 2 accounts for the movement of water molecules through the FO membrane selective layer. The working theory of FO for water purification is depicted in Fig. 1

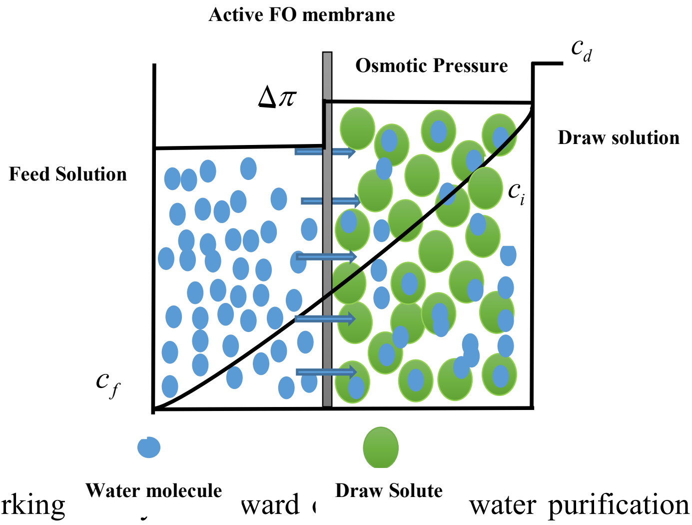

Fig. 1 The working ward water purification. The working theory describes the motion of molecules of water through the FO membrane selective layer. c_f, c_i and c_d are the solute concentrations in the feed solution, at the barricade boundary and in the draw solution

2.1 Concentration polarization (CP)

Concentration polarization occurs during the development of concentration gradients at the crossing point of membrane/solution ensued from targeted transmission of some ions across the membrane in accordance with the influence of transmembrane aiding forces [15]. For FO membrane processes, CP is triggered via the variance in concentration amid the feed and the draw solutions across asymmetric FO membrane. Here, the solution of the feed turn out to be highly concentrated at one side of the membrane and the draw solution turn into highly diluted at the other side of the membrane. Hence, the differential osmotic pressure will be effectively minimized; thereby allowing the solvent to proceed through the membrane. The extent of such effects is dependent on the structure of the membrane and its alignment [16]. Pure water flux is given by Eq. (2) which in reality, the net aiding osmotic pressure goes through the energetic stratum of the membrane. Studies have shown that concrete fluxes are greatly lesser than the predicted fluxes, from Eq. (1) [17]. This is ascribed to the external concentration polarisation (ECP) which transpires on the dense stratum and internal concentration polarisation (ICP) that happens inside the pores of the support layer, as demonstrated in Fig. 2. ICP is considered most vital for FO processes. The ICP of FO process is an irregular occurrence that intensely lessen the difference in concentration through the energetic stratum, regarded as the aiding strength of the separation process. The characteristics of the membrane support stratum assembly and the solute diffusion coefficient influence the capability of the solute to diffuse from the concentrative ICP and into a dilutive ICP through the pores of the support stratum, which take part in the extent of controlling the ICP [17]. *K,* which is the term representing the solute resistance to diffusion in the membrane support stratum, has been represented by Eq. 3 [18]:

$$K = \frac{t\tau}{D_b \varepsilon} \tag{3}$$

here K denotes mass transfer coefficient, D_b denotes bulk diffusion coefficient of the solute while t, τ, and ε, stand for thickness, tortuosity, and porosity of the support stratum, respectively. The reduction in osmotic pressure difference via the osmotically-energetic barricade stratum by the ICP, is to a larger or smaller degree dependent on the trans-membrane volume flow. Therefore, an alternative which is a straight line dependence of osmotic-pressure difference amid the solutions is given; hence, the flow usually show a decelerating, log-likelihood reliance on it [19]. A satisfying FO membrane offers an intense water permeability, retention of solutes that is high enough, significantly decreasing ICP, with elevated chemical stability and mechanical strength [20].

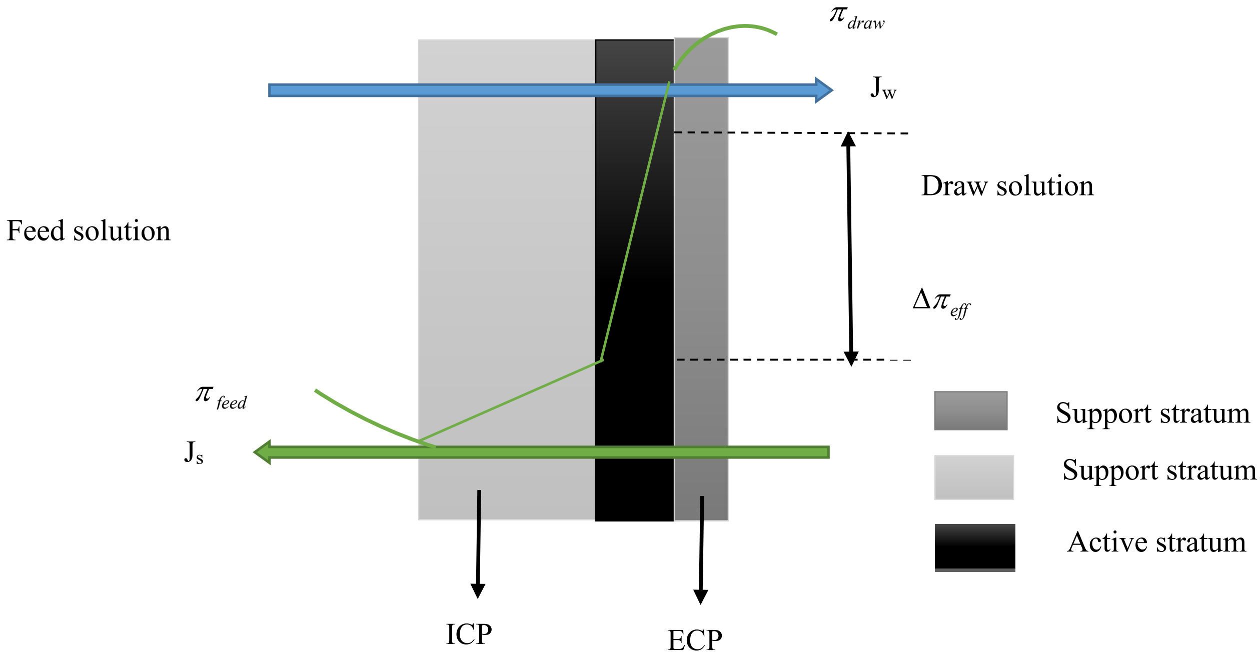

Fig. 2 Schematic representation of ICP and ECP across asymmetric FO membrane. ICP takes place inside the membrane support stratum, and ECP is present at the surface of the membrane energetic stratum. J_s, J_w, $\Delta\pi_{eff}$, π_{feed} and π_{draw} represent the solute flux, water flux, the effective aiding force, the feed solution concentration and the draw solution concentration respectively (Modified Ref. [21]).

2.2 Draw Solution

The aiding strength for separation in FO is the gradient of the osmotic pressure; thus a very most important component which must be present with the purpose allowing the process of forward osmosis to occur efficiently is known as draw solution. A high concentrated draw solution that is in relation to the feed solution, is employed to urge the flow of liquid across the membrane into the draw solution; hence, efficiently separating the feed from its solutes. FO processes could have solute diffusion in both ways; that is the draw solution solutes could diffuse to the feed solution and the solutes could diffuse to the draw solution [14], [22]. This is reliant on the feed water composition and the draw solution. These occurrences will obviously have aftermath with respect to the choice of draw solution for every precise FO process. An example is the reduction of draw solution which could influence the feed solution possibly owing to ecological concerns or pollution of the feed stream [16]. It is a must for a satisfying draw solution to possess the resulting features: intense water flux, negligible reverse draw solute flux, free of toxics, easy recovery and a reasonably low cost [20]. Again, it is essential that the draw solute should be well-suited with the FO membrane, thus the obtainability of a right draw solution is very essential for the improvement of FO processes. The draw solution should have the capability of producing a elevated osmotic pressure; it is thus essential that the osmotic pressure of a draw solution to be greater than the osmotic pressure of the feed solution for the purpose of ensuring a positive permeate flux [20]. A proper draw solution stimulate the effectiveness of the FO process and avoids unnecessary costs at the later stages in order to recover and replenish the draw solute. Investigations on suitable draw solution for FO process have, lately been published in accordance with different design approaches. An example is the use of magnetic nanoparticles with improved surface hydrophilicity or stretched molecular size [23], [24]. Different types of draw solutions have also been reported depending on physicochemical properties [25]. Some researchers have also reported organic compounds with enhanced volatility [26], [27]. A draw solute should also possess a slight to moderate molecular weight and low viscosity in order to have high diffusion coefficient and reduce ICP.

3 Pressure retarded osmosis (PRO)

PRO is regarded a transitional process amidst FO and RO, during which a hydraulic pressure difference (ΔP) lesser than the gradient (Δπ) of osmotic pressure through the membrane is employed in the other path of osmotic pressure gradient on high salinity draw solution. PRO makes use of the advantage of the difference in osmotic pressure that over time progresses due to separation of two solutions with diverse concentrations at the semipermeable membrane. Water permeates from the dilute feed solution to highly concentrated draw solution by virtue of the difference in osmotic pressure [28]. Nonetheless, the total flux is towards the concentrated draw solution; this characteristic is analogous to FO [29]. Fig. 3 and Eq. 19 illustrates the water transport that describes PRO process.

$$J_w = A(\Delta P - \sigma\Delta\pi) \qquad (19)$$

where σ denotes reflection coefficient, and ΔP stands for trans-membrane hydraulic pressure, $\Delta\pi$ denotes difference in osmotic pressure. ΔP in FO is negligible (ΔP=0), and it must be greater than $\sigma\Delta\pi$ in RO in order to produce purified water, thus for RO, $\Delta P > \Delta\pi$; and for PRO, $\Delta\pi > \Delta P$ [28, 14]. Driven by Δπ-ΔP, water spontaneously permeates from a low-salinity feed to the pressurized high-salinity draw solution via the semipermeable membrane with at a flow rate of ΔV .

$$\Delta V = J_w \times SA_m \qquad (20)$$

where SA_m denotes membrane surface area and J_w denotes water flux.

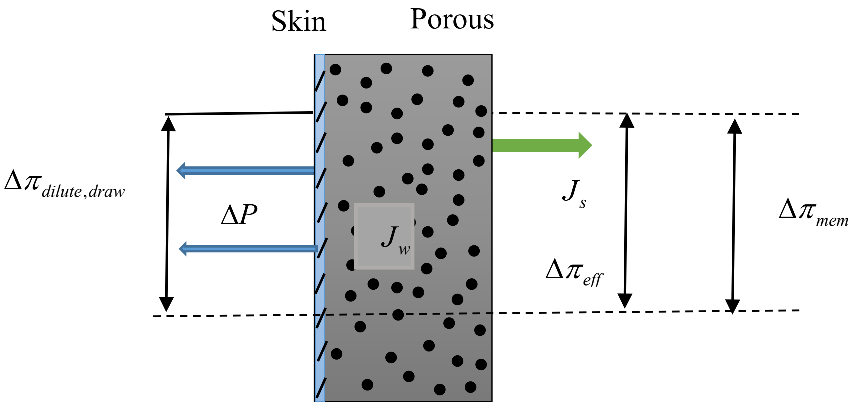

Fig. 3 Description of PRO. $\Delta\pi_{mem}$ is the difference in the osmotic pressure through the membrane, $\Delta\pi_{eff}$ denotes active osmotic pressure gradient through membrane selective

stratum, $\Delta\pi_{dilute,draw}$ is osmotic pressure amid the dilute feed solution and concentrated draw solution.

There will be an upsurge in pressure at an elevated pressure section, as a consequence of the flow of permeate across the membrane to the other. Again, salt water will be enlarged as a result of more volume (ΔV) coming from the low pressure section. Consequently, it is diluted to a new solution characterised as brackish water [30]. Continual flux (J_w), subsequently upsurges the volume of the pressurized water in the compartment of the draw solution and could be heading for to an energy recovery device like turbine for electricity generation [31].

4 The uses of osmotically driven membrane processes

The applications of osmotically aided membranes processes will be discussed in this section.

4.1 Uses of FO membrane process

FO membranes possessed exceptional features, allowing effective diffusion of water across the polymeric membranes. Such features comprise of a very active thin and porous support layer having pores with less tortuosity. FO is an outstanding innovative technology with the capacity of eliminating stubborn contaminants from industrial waste streams. FO has recently gained interest as a result of its prospect in utilizing it for seawater/brackish desalination [32], [33], treatment of wastewater [34], [35], processing of food [36], [37] and power generation [38]. This technology can also be applied to Dewatering of sludge, oil and gas exploration, membrane bioreactor etc.

4.1.1 FO for seawater/brackish desalination

Seawater/brackish desalination using FO process includes water absorption and water recovery. Thus, FO membrane technology employed for seawater desalination comprises of two important stages: (1) removal of water from the seawater via a draw solution, and (2) separation of the product water from the diluted draw solution through the use of nanofiltration (NF) [38], [39], ultrafiltration (UF) [40], RO [41], [42], and other thermal methods [43]. The above listed processes use a lot of energy either via hydraulic pressure or the use of energy through heating, as it is a requisite that must be considered re-concentrating the diluted draw solution. As consequence, uncomplicated regeneration of draw solutions is extremely important for the purpose of reducing the consumption of energy and total costs of operation. The desalination of FO process without other filtration methods has been comprehensively researched owing to its potential in reducing total consumption of energy for the purpose of producing potable water [44].

Dense semi-permeable membranes are the most obtainable membranes for the application FO process; these membranes are gotten from RO industry. However, Most FO investigations done on the use of RO membranes have shown ample lesser flux than anticipated [45], [46]. The suitable FO desalination process must possess zero-liquid discharge (ZLD) which needs a much higher water recovery. In addition, a much higher water recovery is only attainable at large osmotic aiding force. Therefore, a suitable draw solute should have the capability of producing much higher osmotic pressure at low concentration. This means that an ideal draw solute much more soluble in water and possess low molecular weight [47]. A non-edible draw solution should be recovered from draw solution at the conclusion of FO process. Hence, an economical draw solute is required in order to be removed then further reused. It is a very vital measure as the FO consumption of energy is principally connected to the draw solution re-concentration. In addition, chemically inert draw solute to the membrane is necessary for the purpose of non-reaction or non-degradation, and non-toxic for human consumption because some trace amounts could exist in the water produced [48].

Investigation on seawater desalination previously done by using FO process mostly has to do with the choice of draw solution and recovery of flux [49]. Nevertheless, because of the fouling tendency of seawater on the FO membrane, it is required that any seawater should be pre-treated before transporting it across the FO membrane. Understanding the assessment of the fouling activities throughout the osmotic dilution of seawater as portion of the concurrent desalination and wastewater reuse in the FO process was recently investigated. The influence of various working factors such as cross flow rate, pH of feed water, applied pressure, on the fouling propensity has been reported. To this end, several fouling alleviation approaches has been recommended for the purpose of optimising the longstanding FO processes [50]. Longstanding experiments have shown that stimulating water flux configuration depend more on the various working factors. The utmost remarkable observation was the spur-of-the-moment in the FO permeate flux at steady time intermission throughout FO process by employing simulated wastewater as feed and seawater. Though fouling of FO membranes is less severe in comparison to other pressure aided membrane processes owing the aiding strength of FO is the osmotic pressure. Hence, the process operates at a small or zero hydraulic pressure, which lessened the amount of observed fouling and permits membrane to operate with a fairly sparse support structure. Some fouling can still occur, but they relies on the category of feed solution together with draw solution, but by reducing fouling, increased FO membrane performance can be expected, thereby increasing the economic viability of FO processes. During desalination, the reliance on osmotic pressure makes it the major factor in the choice of the draw solution [29].

4.1.2 FO for wastewater treatment

Wastewater comprises of different types of contaminants that might be harmful human health. The presence of some of these compounds in reclaimed water has been the challenge in portable water. The metals in contaminated water occurs in their ions and in the form of dissolved salt. Traditional technologies for treating such salts are coagulation, flocculation, chemical precipitation, floatation, ion exchange, electrochemical processes and adsorption [51]. FO has the prospective to a long lasting treatment of wastewater sources for the purpose of producing high quality water in comparison to these traditional technologies. FO is dependent on the difference in osmotic pressure through the membrane to produce fresh water from contaminated water [52].

A desirable draw solution for FO process is also very important for the purification of polluted water for the purpose of having (1) much more osmotic pressure to yield a much higher flux, (2) negligible reverse draw solute flux, (3) uncomplicated reinforcement from the diluted solution, (4) nontoxicity and conformable with the FO membrane [53]. Few years ago, inorganic salts, like NaCl, KBr, $MgCl_2$, $MgSO_4$, $CaCl_2$, and $((NH_4)2CO_3$ have been the most investigated draw solutions used in FO processes. This is because they possessed solubility at a greater extent and much more osmotic pressure that result in a high water production. Nevertheless, a lot is required of reverse osmosis for water recovery, high reverse salt diffusion, diluted draw solution concentration and salt leakage are regarded the chief shortcomings that stalled the application of these draw solutes. The diffusion of the draw solution to feed solution have the capacity to minimize the total osmotic aiding strength and prompt fouling on the supported stratum of the membrane, this will eventually lead to flux reduction. Furthermore, the build-up of the draw solute in the feed solution have the capacity to change the nature of the feed [54].

In order to overcome salt leakage and the many demands of reverse osmosis used for the recovery of water, different kinds of novel draw solute have consistently been examined during the past decade. Functionalized nanoparticles with magnetic properties, as a prospective draw solute has been investigated as a result of their capacity to minimize reverse flux and be recovered without difficulties with the aid of external magnetic field; as a result, the intake of energy was minimal in the process of regenerating the draw solute [55]. Nonetheless, the shortcoming of this draw solute was the clustering of the particles in the process of the recycling. Generally, wastewater has lesser osmotic pressure and greater fouling susceptibility [56]. FO membrane fouling proneness for the treatment contaminated water should to be addressed carefully for the purpose of having a speedy movement of water to the draw side, without the motion of solutes amid the draw and feed solutions, particularly it use in closed-loop systems. Thus, FO membrane technology used for treatment of contaminated water should comprise of a dense, ultra-thin, energetic-separating stratum with stable mechanical properties, satisfying a prolong working process and decreasing ICP which will in turn result to an acceptable solute rejection, improved water flux and decreased fouling susceptibility.

4.1.3 FO for food processing

Numerous beverages and food processes undergo concentration or evaporation phase during processing in order to last sufficiently enough for transportation, storing and to be suitably distributed for used as constituent in other products. FO employs membranes to concentrate liquids and it greatly utilizes minimal pressure and low temperature than evaporation, thus it uses less energy and most importantly less fouling thus, easier cleaning. The processing and preservation of food technologies should sustain the fresh-like features of food in order to provide a satisfactory and suitable shelf life together with guaranteeing safety and nutritional value. Proteins stay undamaged and components like vitamins, flavours and aromas are reserved because FO process does not use heat; thus, food products can have healthier qualities. In addition, the demand of consumers for the healthier qualities and suitable foods with respect to expected flavour and taste, without condiments and preservatives compelled the novel progress of membrane-based non-thermal methods to the concentration of liquid foods, and FO is now confirmed the best technology [57].

One aspect of the utilization of FO in food industries is based on fruit juice concentration [58], [59]. In principle, FO in fruit juice concentration utilizes solution of an osmotic agent (OA) for the purpose of establishing an osmotic pressure gradient via a semipermeable membrane. The most often used components are NaCl, $C_{12}H_{22}O_{11}$, or $C_3H_8O_3$, $C_6H_{12}NNaO_3S$ or $C_6H_{14}O_7$. It is a must for OA solutions to possess an osmotic pressure that is more than the concentrated fruit juice [60]. The differences in pressure through the membrane in FO are very minimal and the water flux is reliant on the osmotic potential difference [61]. Juices that comprise of large quantities of dissolved and suspended solids have the capacity to be concentrated with the lowest fouling due to the fact that the solids are not enforced contrary to the membrane [62].

There are several records on the utilization of FO for liquid food processing, but this section will focus on few investigations of the last decade till date which could lead to the new developments in the subject area. Babu et al. [62] reported the influence of process parameters like the concentration of mixed salt and sucrose, flow rate and temperature of the feed on transmembrane flux using FO. The authors examined the influence of straight osmosis process on different physicochemical features of pineapple juice, like the pH, titratable acidity, ascorbic acid content, colour, density and viscosity. By using a specific membrane for FO (Osmotek Inc., Corvallis, OR), the authors detected a rise in the transmembrane flux for the pineapple juice together with a rise in the solution concentration of for NaCl. When sucrose was used as osmotic agent, there was a rise in the transmembrane flux for the pineapple juice together with a rise in sucrose solution concentration. The rise in flux was ascribed to the upsurge in osmotic pressure difference through the membrane as a result of the rise in the concentration of osmotic agent solution. This led to an upsurge aiding force for the movement of water across the membrane. The authors noticed substantial influence on transmembrane flux and the influence was highly protruding at an elevated feed concentration as a result of the hydrodynamic states on osmotic agent and feed side. They further detected that the transmembrane flux rises with a rise in feed temperature. The combined sucrose-sodium chloride overcame the disadvantage of sucrose having little flux and the salt movement of sodium chloride as osmotic agents throughout the straight osmosis process. Utilization of a flat sheet membrane for a sucrose solution by FO was concentrated employing sodium chloride as a substitute draw solution [36]. It has been revealed by this report, that FO processes could result to sucrose concentration elements that are far more than present pressure-aided membrane processes, like reverse osmosis. In comparison to the concentration factors of up to 2.5 studied with reverse osmosis, a concentration factor of 5.7 with initial sucrose concentration of 0.29 M was attained with the application of FO. Though, in comparison to reverse osmosis, water fluxes were lower; this was due to the magnitude of the substantially greater concentration factors together with internal concentration polarization. Internal concentration polarization is a usual challenge of forward osmosis processes that employs recent generation anisotropic polymeric membranes. Thus, novel developments in FO membrane process should be looked into with the purpose of having acceptable water fluxes and concentration factors. Anthocyanin extract was concentrated from kokum using FO [63]. FO was recently employed to recover and concentrate tuna cooking juice [64]. The authors found that FO process could have the capacity to raise the concentration of protein up to 9% with flux of 2.54 $Lm^{-2}h^{-1}$. However, the flux have a tendency to reduce with a rise in protein concentration as a consequence of the influence of osmotic pressure of the feed and fouling on the external part of the membrane. For the fact that tuna cooking juice comprises of protein and minerals, membrane analyses have shown that fouling was on the high side when compared to the fouling that resulted from standard bovine serum albumin pure protein.

This section has clearly shown that FO displays numerous benefits regarding liquid food processing. These may lead to better preservation of some bioactive compounds such as Citrus aurantifolia, limonene, α-Pinene e.t.c., compared to conventional membrane technology. FO needs zero or lesser hydraulic aiding pressure, thus the prospect of the FO membranes to have lower fouling activities when compared the traditional pressure-driven membrane processes. Nonetheless, different factors such as osmotic agents, membrane orientation, and concentration polarization could lead to some fouling. Most often concentration polarization, most importantly the ICP affects the actual osmotic pressure through FO membrane which is the key aiding force for the filtration process. It is therefore essential to fabricate innovative FO membrane materials with high porosity, low tortuosity and high rejection rate of solutes that will preserve some bioactive compounds in the juice.

4.1.4 FO for power generation

Recently, a sustainable energy source (osmotic energy) with slight ecological effect, has given ample consideration. Membranes processes that are osmotically aided have the capacity to produce osmotic energy which consequently have huge prospect in the production of sustainable clean water and electric energy [49]. The pressure generated in FO for power generation could possibly be controlled for the production of energy [65]. Al-Hemiri et al. [66] investigated the possibility of using osmosis phenomenon to produce energy (that could be in form of a renewable energy) by utilizing Thin Film Composite Ultra Low Pressure membrane TFC-ULP. In their investigation, forward osmosis water passes from side of the membrane to the concentrated brine solution, which could result in raising the head of the high brine solution. The process as a source of renewable energy was very promising, however, with the results obtained, it was beyond achieving. PRO is the main process used in generating energy from osmotic pressure differences, though FO system which have the capacity of running in PRO approach can likewise have the capacity to be employed for both osmotic power generation and process optimization at industrial level. The intention of such process is to co-localize desalination plants and treatment plants for contaminated water; and employ the brine waste from the desalination plant to both dewater wastewater streams and concurrently produce electricity via PRO [65].

4.2 PRO for power generation

The control and the reduction of greenhouse gasses instigated by burning fossil fuel together with the swift increase in universal energy intake and greenhouse gas emissions have motivated some investigations on renewable energy sources as substituted fuels. These greenhouse gasses, constitutes serious environmental impacts, especially in the form of global warming, to the community. Besides, the present application of fossil fuels like oil and natural gas will lead to an predicted depletion from 2050 onwards [67]. Thus, the reason of using alternative sources of energy that will solve the problem of energy demand world-wide and gradually divert fossil energy sources that will prevent global warming and several other environmental contaminants.

PRO process that produces energy from salinity gradients, is membrane-based [68]. The energy of the osmotic pressure gradient unrestricted from the mixing of water streams with diverse kinds of salinities is an untapped resource of renewable energy. The utilization of a semipermeable membrane in order to control the mixing process, leads to harvesting the osmotic pressure gradient energy with respect to electrical power through PRO without instigating adverse environmental effects [69]. This process could be employed to produce power from the salinity gradient energy ensuing from salt concentration difference amid sea and river water; which appears as a chemical potential difference, for the purpose of producing an intense volume and a high pressure stream. The quantity of fluid volume that is obtainable is reliant on a salt concentration in a salty stream, and is empowered via the osmotic pressure. Nonetheless, the upsurge in the osmotic pressure leads to an upsurge in the quantity of the water or fluid flowing through a membrane. This is consequently likely to control the variance in salinity amid the oceans and rivers or seas and rivers in order to produce electricity, which significantly help in decreasing the demand on fossil fuels [70].

The PRO power plant majorly comprises of the following: (i) PRO membrane module and (ii) hydro-turbine system used in converting the hydraulic energy to electricity [71]. The principle of power production by PRO is shown in Fig. 4. Here, concentrated seawater and diluted fresh water such as river water are separated by a semipermeable membrane, the mechanism of the process allows the diffusion of water from the feed side into the draw solution side, such as seawater side and then pressurized. For the purpose of recovering the hydraulic energy produced, the pressurized diluted seawater will be divided into two streams: a part moving via a hydro-turbine to produce electric power, and the other part moving via a pressure exchanger for the purpose of assisting in pressuring the inlet seawater, thereby, sustaining the circulation [72].

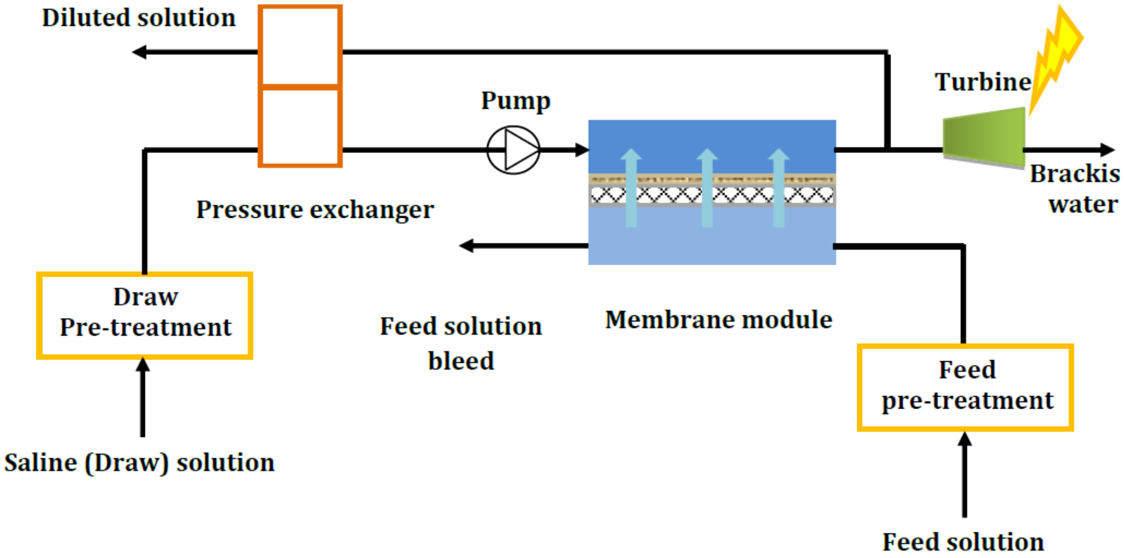

Fig. 4 Illustration of a PRO power plant. Concentrated seawater and diluted fresh water are separated by a semipermeable membrane [73].

The notion of collecting energy produced during mixing of fresh and salt water was first introduced in 1950 by Pattle [74]. Pattle reported osmotic energy and semi-permeable membrane can be employed to generate power by mixing freshwater and saltwater. In his description, he made it clear that, for the mixture of a volume V of a pure solvent with an intense volume of a solution with osmotic pressure π, the free energy released represented by πV. Since the 1970s, PRO has been considered to have a great prospect for a sustainable energy source and as a possible contributor to desalination systems as researchers started the use of this concept for the likelihood of utilizing PRO to produce energy two decades later [68], [75-77]. The concept was later developed by Loeb [78] who anticipated the use of salinity gradient for the generation of power, he found that the generation of hydroelectric power by PRO at Great Salt Lake (GSL) could be practicable with spiral module membranes using water from a river which would permeate into pressurized 12% brine from half of the lake. The cost of energy would be basically dependent on achieving satisfactory permeate flux across the membranes and the author concluded that the principal hindrance is the resistance to solute diffusion in membranes with porous substructure. PRO membrane fouling is very complex when compared to the fouling in FO, this is because with regards to PRO operations, the feed stream faces the porous substrates. Furthermore, the reverse salt flux could accelerate fouling and cause complication in fouling mechanisms [79], [80]. Major developments have been made for the purpose of advancing a novel membranes designed and fabricated for the PRO process [28], [70], [81-82].

Hollow fiber membranes that possess anti-fouling features for osmotic power production have been fabricated by attaching hyper branched polyglycerol (HPG). The poly(ether sulfone)-thin film composite (PES TFC) membrane attached by HPG has an intrinsically higher water flux, a higher power density and shows a superior flux recovery (94%) after cleaning. Therefore, by attaching the suitably designed dendritic polymers to the membrane support, PRO hollow fiber membranes used for the generation of power will be extensively sustained [83]. In order to reduce or eliminate fouling, PRO thin-film composite (TFC) membranes was recently restructured by integrating distinct zwitterionic copolymers of [2-

(methacryloyloxy) ethyl] dimethyl-(3-sulfopropyl) ammonium hydroxide (DMAPS) or 2-methacryloyloxyethyl phosphorylcholine (MPC) onto the poly(ether sulfone) (PES) hollow fiber membranes [84]. The TFC-PES membranes attached by zwitterionic DMAPS and MPC copolymers displayed considerable enhancement with regards to flux recovery (98%) after backwashing. The investigation was summarized thus: The osmotic power generation have the capacity of sustainability by attaching the PRO membranes with a proper zwitterionic polymers design. However, PRO membranes exhibiting greater power density, having the capability to endure greater pressures and an improved anti-fouling characteristics are required promptly [85].

5. Most important hindrance to osmotically driven membrane processes

Unavailability of suitable membranes is the most impairment to the development of suitable membrane processes for seawater/brackish desalination, treatment of contaminated water, food processes and the production of power from salinity gradients. The support layer of FO and PRO intensely influences the mass movement of solutes, this greatly affects the performance of membrane. The ICP discussed in section 2.1 was used to explain the occurrence of ICP and is partially built on the structural features of the support that hinder diffusive transport [86]. Investigations regarding the fabrication of suitable membranes for FO processes have been reported [87-89]. Investigation done on the mass transport resistances related to the asymmetric support layers in FO and PRO have been extensively reviewed. The review was based on the impact of the characteristics of support stratum on the efficiency of asymmetric membranes in pressure aided applications [86]. The power generated per unit membrane area (power density) in a PRO process, accounts for the extent of salinity energy conversion to useful work; this also depend on the type of membrane used. An elevated power density is preferred for the purpose of reducing capital cost connected to the membrane modules. Having twice the power density needed to halve the membrane area necessary to produce the same power, is an example [90]. Investigation have shown that the application of PRO for the production of power is dependent on the membrane power density [72], [91], [92]. Specifically, it is necessary for the power density to be greater than 5 Wm^{-2} for seawater-river water in order for PRO power generation to be cost-effective [93]. Nevertheless, research has also shown that commercially obtainable thin-film composite polyamide RO membranes and integrally-skinned cellulose acetate membranes both attained power densities significantly lesser than the 5 Wm^{-2} yardstick, with the demonstration of Norwegian PRO plant generating less than 0.5 Wm^{-2} employing the asymmetric cellulose acetate membranes [94], [95].

The membrane materials and features can intensively impact on membrane fouling. The FO/PRO membranes employed are usually made of a nonporous having effective stratum with high ion rejections and a porous support stratum that enables the movement of most ions and solutes [28], [79], [95]. Fundamentally, the separation features of the effective stratum and structural features of the support stratum direct the transportation of water and solute. This have the capacity to improve the impact of the behaviour of the membrane fouling. Fouling of osmotically driven membrane processes (ODMPs) was recently lengthily revised with respect to the existing literature [96]. The report started with revising of the basics of mass transport in ODMPs. A proposed osmotic-resistance filtration model differentiating all the aiding forces for the over-all debate of membrane fouling in ODMPs was then reviewed. Structural features of membranes could greatly have effect on the internal fouling in the applications of PRO. Membrane fouling is inevitable in osmotically aided membrane processes. Nevertheless, they could be reduced by developing desirable membranes for ODMPs. Thus, it is very important to give attention to the structural properties of membranes when designing membranes for FO/PRO applications.

6. Recent Advances

The two osmotically driven polymeric membrane processes reviewed here, have demonstrated prospective applications in food processing, seawater/brackish desalination, treatment of contaminated water and the generation of power. Apart from the suitable design of membranes, the performance of osmotically aided membrane processes also results from the important combination of external test parameters like membrane orientation, osmotic strength of the feed and draw solutions, molecular nature of osmolytes e.g. MgCl, flow velocity, flow conditions and the experimental design. The overall efficiency of the FO process includes its flux and productivity, but membrane fouling restricts its large-scale applications. Because the occurrence of the CP is instigated by features intrinsic to the FO membrane which is difficult to eliminate, novel developments in the FO process need a comprehensive insight in CP and technical progresses justifying its deleterious impacts [97]. For the purpose of increasing the performance of FO, many strategies were tried, such as the fabrication of diverse membrane materials, synthesis of membrane modules, membrane coatings, and scaling control to minimize the membrane fouling in FO.

Gwak and Hong [98] recently suggested an innovative methodology to scale control in FO by utilizing an anti-scaling blended draw solution. For the purpose of evaluating the strength of this approach, an anti-scaling blended draw solution made of mixed NaCl and PAspNa was studied with reference to gypsum scaling at several functioning modes. When likened with a draw solution made only of NaCl, the PAspNa-blended draw solution revealed flux that is comparable but with lesser reverse solute flux. The assessments of Gypsum fouling revealed that reversely flowed polymeric anions from the blended draw solution have the capacity of efficiently controlling membrane scaling, with a scaling hindrance effectiveness equivalent to the direct addition of PAspNa to the feed solution. The overall findings have shown that this novel scaling control approach in FO can be stretched to several anti-scalants that are enhanced for exact mineral scales. Therefore, FO have a very high prospect for commercialization.

With respect to membrane orientation, a study was recently carried for the purpose of increasing the membrane hydrophilicity and hence, lessen the ICP. Polyethersulfone was chosen to be an effective support stratum and treated with nanoparticles of diverse surface features. ZnO and stable ZnO-SiO_2 core-shell nanoparticles were well homogenously distributed in the polyethersulfone solution. Consequently, a thin effective stratum of polyamide was placed on it in order to attained support stratums via the use of interfacial polymerization method. The characterizations done showed the main influence that the properties of nanoparticles surface had on the structure of cross-section pores, these were moulded within polyethersulfone support stratums. High permeate flux enhancements were experienced in the membranes amended with ZnO-SiO_2 core-shell nanoparticles. Hence, nanoparticles can be a prospective nanofillers to enhance the efficiency of FO membranes [99]. Recently, another study successfully blended Na type ion exchange resin (IER-Na) powders into the support stratum of FO membrane. This can bring about an additional charged pathway. Subsequently, the flux of 5wt%IER-Na (with 5 wt% IER-Na loading) was higher than that of 0wt %IER-Na (with 0 wt% IER-Na loading). Notably, the salt rejection was retained above 95.0%. The study demonstrated that the improved water flux could be ascribed to the additional charged pathway presented by IER-Na. At the same time, the salt retention retained was attributed to the substantial salt retention of additional charged pathway introduced in IER-Na. The study revealed the insight on a new potential in promoting the mass transfer in FO membranes [100]. A recent study prepared a thin film composite (TFC) FO membrane made of three layers for the purpose of concurrently reducing the ICP and improve the mechanical stability of FO membrane. Factors such as polymer concentration, coagulation bath composition and the gate height of the casting blade that influence the formation of the mid-stratum structure were examined. The water flux in the range of 10.39 to 30.62 LMH was attained by employing 0.5 M NaCl draw solution and deionized water feed solution in the mid-layer of FO membrane cast under diverse conditions. The authors concluded that TFC FO membrane with great structure reliability could be a potential candidate for a novel osmosis [101].

The concentration and solution chemistry of the solute always aid the potential to generate energy through the diffusivity of the solute and the suitable choice of membrane for that solute which will govern the transport. The potential of three inorganic draw solutes; NaCl, $MgCl_2$ and $MgSO_4$ was recently evaluated for their application in osmotic heat engine (OHE) during PRO. Power densities over 13 Wm^{-2} and 14 Wm^{-2} were attained with respect to $MgCl_2$ and NaCl respectively. Nonetheless, NaCl gave a much higher salt flux than $MgCl_2$. Significantly lower power densities were attained by $MgSO_4$. The differences in power density might be partially ascribed to the differences in hydrated ion radius which greatly influenced the reverse solute flux and further development of ICP [102].

7. Model Development

Modelling is a tool that can be employed to envisage the efficiency of membrane, to disclose separation mechanisms, to choice proper membranes, and to design processes [103]. Improved models for envisaging the efficiency of osmotically driven membrane processes should employ available property data, like membrane thickness, pore radius, and electrical parameters e.g., the surface charge density and the volumetric charge density, and solute properties such as the solution chemistry of the draw solute. It is hence, essential to develop a predictive mathematical model that will describe membrane with respect to parameters that would be useful in the predictive models. Theoretical models and equations can be used to describe the osmotic pressure, osmotic force for the transportation of component (which is the gradient in free energy) and different ideal draw solution concentrations for different application, which can overcome the limitation of osmotically driven membrane processes.

8. Conclusion

Osmotically aided polymeric membrane processes have gained interest as green technologies that offer uncontaminated water and energy. The paper review the assessment of the efficiency of osmotically aided polymeric membrane processes. Novel strategies should be made continually with the aim of enhancing the efficiently of osmotically driven membrane processes which employs osmotic pressure of the draw solution as the aiding force. The ICP transpires within the porous support stratum but the extent of this effect solely rest on the type of the membrane and its orientation because of the membrane active layer. Thus, efforts should be made on linking the pores in support stratum with porous materials in order to alleviate the ICP in support stratum. Selecting an efficient support layer and treating it with nanoparticles in order to introduce nano-pathway with high salt retention is very important.

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